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LOW-GRAVITY VENTING OF REFRIGERANT 11

by Thomas L. Labus, John C. Aydelott, and Raymond F. Lacovic

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16. Abstract

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SUMMARY

An experimental investigation was conducted in the Lewis Research Center's 5-Second Zero-Gravity Facility to examine the effects of venting initially saturated Refrigerant 11 from a cylindrical container (15-cm diameter) under reduced gravitational conditions. The system Bond numbers studied were 0 (weightlessness), 9, and 63 and the liquid exhibited a near zero-degree contact angle on the container surface. During the venting process, both liquid-vapor interface and liquid bulk vaporization occurred. The temperature of the liquid in the immediate vicinity of the liquid-vapor interface was found to decrease during venting while the liquid bulk temperature remained constant. Qualitative observations of the effects of system acceleration, vent rate and percent vapor volume are presented. Also included are quantitative information concerning the ullage pressure decay during low-gravity venting.

INTRODUCTION

In support of the NASA space program, Lewis Research Center has been conducting experimental research dealing directly with problems involving heat transfer, fluid mechanics, and thermodynamics in reduced gravity environments. As a part of this overall research effort, an investigation of liquid behavior during the venting of saturated vapor under reduced gravitational conditions has been initiated.

The use of cryogenic propellants has resulted in problems of propellant management (refs. 1 and 2). During missions in space, cryogenic propellant tanks will require periodic venting, as the tank pressure increases due to various heat inputs, to allow the tank pressure to remain within predetermined limits. The current technique for venting orbital propellant tanks involves the use of settling rockets to position and maintain the liquid-vapor interface away from the vent (ref. 3).

Since settling rockets are employed for liquid-vapor interface positioning, efforts are made to minimize fuel requirements by utilizing short vent times. Unfortunately,

in low gravity, minimizing the vent time (maximizing the vent rate) may have an adverse effect on the behavior of the liquid during the vent period.

The two major mechanisms affecting depressurization rates during venting under all gravitational conditions are expected to be the boiling occurring in the bulk liquid and the vaporization occurring at the liquid-vapor interface. Interface vaporization appears to occur for any infinitesimally small temperature difference between the liquid bulk and the liquid-vapor interface. On the other hand, for boiling a finite temperature difference must exist between the initial saturation temperature of the liquid and the saturation temperature corresponding to the reduced pressure (commonly termed degree of superheat).

In normal gravity, the venting of saturated vapor reduces the tank pressure to below the saturation pressure of the liquid; hence, vapor can be generated both at the surface and in the bulk of the liquid. Under normal gravity, the vapor generated in the bulk rises and subsequently erupts through the liquid-vapor interface to join the tank vapor. If the depressurization rate is too large, the possibility exists that the vigorous boiling and resulting breakthrough of vapor at the liquid-vapor interface can result in liquid droplets being vented along with the vapor.

In zero gravity the vapor generated in the liquid bulk does not rise because of the absence of buoyancy forces and instead expands the liquid bulk causing the interface to move toward the vent. In the extreme, this can cause loss of liquid through the vent.

Good examples of the liquid behavior in low-gravity venting are presented in references 4 and 5, in which the liquid hydrogen behavior during the orbital flight of the AS-203 S-IVB was discussed. The generated vapor from bulk boiling in low gravity will not rise as quickly due to the reduction in buoyancy forces. For a given vent rate, there exists some demarcation in gravity level below which vapor generated in the bulk will not break or disrupt the liquid-vapor interface. This is a complex phenomena and no information is available to predict this demarcation in g-level. It is suspected that initial vapor bubble location, size, rate of growth, inherent oscillations of the vapor bubbles themselves and liquid and vapor properties will all determine the breakthrough of saturated vapor at the liquid-vapor interface.

An experimental drop-tower investigation of venting was conducted by Larkin and Bowman (ref. 6). Venting of Refrigerant 11 and liquid hydrogen was conducted in weightlessness. The vent rates were not specified (but they appeared to be on the order of one ullage volume per second) and, in addition, no time was allowed for the zero-gravity liquid-vapor interface formation because of drop tower limitations. It was concluded, that in weightlessness, a maximum of one ullage volume of vapor can be vented before any liquid is lost and that the vapor bubbles tended to remain in the vicinity of their nucleation sites.

Neither the flight nor the drop tower experiments provide a complete understanding of the fluid behavior during a low-gravity vent period. Therefore, the NASA Lewis Research Center has initiated a program to experimentally examine the resulting behavior when an initially saturated liquid is vented under reduced gravitational conditions. It will be the purpose of this report to investigate the effect of system variables (Bond number, vent rate, and percent vapor volume) on the venting of a liquid from an initially quiescent equilibrium configuration. The vent rates chosen for this program were much more representative (of order 0.1 ullage per second) of the vent rates expected during space missions than the vent rates used in the tests conducted by Larkin and Bowman (ref. 6) (about one ullage per second).

APPARATUS AND PROCEDURE

The Lewis Research Center's 5- to 10-Second Zero-Gravity Facility was used to obtain the experimental data for this investigation. A complete description of the facility, the experiment package, and procedures for conducting the tests can be found in the appendix. The venting tests were conducted with a cylindrical container that had a hemispherical top as shown in figure 1. The test cylinder had an inside diameter of 15 centimeters and was 30.1 centimeters in overall length. The cylinder was fabricated from acrylic plastic.

The liquid used in all the tests was Refrigerant 11 (trichloromonofluoromethane). The primary reason for using this fluid is that it is a saturated liquid at room temperature. Of secondary importance is the fact that most of the significant thermodynamic properties of Refrigerant 11, such as enthalpy, specific volume, and entropy, can be found in standard refrigeration tables. Third, it possesses a nearly zero-degree static contact angle on the test container surface and is, therefore, representative of typical liquid propellants. A small quantity of dye was added to improve the photographic quality. The accuracy of all temperatures quoted in this report is conservatively estimated to be ±1.5 K while the accuracy of all pressures is estimated to be ±1 newton per square centimeter.

RESULTS

In table I, a presentation is made of the tests conducted and the experimental parameters varied in this program. The three major parameters affecting the venting process include the percentage vapor by volume, Bond number and the mass flow rate during venting. The average mass flow rate for each test was computed by integrating the

curve displaying mass flow rate versus time. Since only one fluid (Refrigerant 11) and one tank size (15-cm diameter) was used, the system Bond number is thus determined by the change in system acceleration alone. The system Bond number is defined as the ratio of acceleration to capillary forces and is a direct measure of the shape of the liquid-vapor interface provided that the contact angle is known. The contact angle of Refrigerant 11 on acrylic plastic is near zero degrees. Parametrically, the Bond number is defined as aR^2/β where a is the system acceleration, R is the tank internal radius (7.5 cm), and β (12.2 cm^3/sec^2 at 298.3 K) is the specific surface tension. The larger the Bond number, the flatter the liquid-vapor interface. When bulk boiling occurred, the generated vapor remained below the liquid-vapor interface thereby moving the interface towards the vent. The data for the estimated amount of vapor generated in the bulk is only approximate due to distortion of bubbles (nonspherical) and refraction caused by viewing through the container walls and liquid.

If table I is now examined, it can be noted that a 30 percent vapor volume, a Bond number of 9, and a vent mass flow rate of approximately 0.5 gram per second were the base values of the tests conducted. All the tests will now be discussed in detail and test 1 will be discussed in the most detail since it illustrates the typical fluid behavior for all the tests.

Test 1

In figure 2, the photographs showing the venting of Refrigerant 11 in low gravity are displayed. The system Bond number for this test was 9 and the average mass vent rate was 0.53 gram per second. In figure 2(a), the initial configuration of the test liquid is shown prior to entering a low-gravity environment. An initially saturated state of Refrigerant 11 was obtained by repeatedly venting and then allowing the system to stabilize (see appendix). The tank internal pressure and temperature were monitored during this procedure. After the liquid reached nearly saturation conditions (0.88 atm and 290.9 K for this test) the container was placed into a low-gravity environment. One second was allowed for the formation of a low-gravity interface as shown in figure 2(b). At 1.01 seconds after package release, the vent was opened to vacuum thereby initiating the venting sequence. Surface irregularities were observed to occur in both figures 2(b) and (c). In the center of the test container, a hump appears as a result of the liquid-vapor interface formation mode and liquid can be observed clinging to the two temperature probes due to surface tension effects. The vent remained open 3 seconds during which time the photographs, shown in figures 2(d) to (f), were recorded. Vaporization occurred starting from the initiation of venting and continued throughout the test. Figure 2(d) indicates the initiation of bulk vapor generation. The hump associated with the interface formation mode had vanished by this time. The majority of bulk vapor gener-

ation started at approximately 2.8 seconds. In figure 2(e), bulk vapor generation is shown. The distortion slightly above the visible liquid-vapor interface is typical of the interface motion which occurred throughout the test. In figure 2(f), the photograph of the configuration prior to the termination of vent is shown; the generated vapor bubbles are shown to be moving slowly towards the liquid-vapor interface due to buoyancy forces. Thirty small vapor bubbles, constituting in an estimated 16 cubic centimeters of vapor, were generated in the bulk during the 3 seconds of venting. This is approximately 0.077 gram of vapor generated and is significantly less than either the initial vapor mass or the total mass vented. The ullage pressure response during venting is shown in figure 3(a). The pressure dropped 1.3 newtons per square centimeter during 3 seconds of venting. In figure 3(b), the vent mass flow rate in grams per second is shown plotted as a function of time. It is not constant because the tank pressure is decreasing. In terms of the initial ullage vapor mass, the average vent rate represents about 6.9 percent ullage vented per second.

The bulk temperature (as measured by a thermistor located near the bottom of the test container) and the temperatures in the vicinity of the liquid-vapor interface were monitored. During the venting sequence, the bulk temperature remained constant, unaffected by the venting. The surface temperature probe was initially located slightly below the liquid-vapor interface. At some time later during the formation mode and also during the vent, the liquid surface would alternately cover and uncover the probe. This temperature yields an indication of the temperature response of the vapor in the vicinity of the liquid-vapor interface. With reference to figure 3(c), it can be seen that this temperature decreases during a venting sequence. The fact that the temperature dropped 0.55 K during the no vent period (0 to 1 sec) is thought to be the result of a slight non-equilibrium condition.

Test 2

The second test consisted of an initial 30 percent vapor volume and an average ullage vent mass flow rate of 0.53 gram per second; these two conditions being similar to test 1. However, no acceleration was applied which resulted in a zero Bond number. The interface shape at equilibrium for a liquid possessing a zero-degree contact angle on the container surface is hemispherical (the result of the fluid seeking a shape whose total energy is a minimum). Since this was the only zero Bond number test, it possessed the largest interface area (exposed surface) for venting. In this test, no bulk vapor generation was observed throughout the vent sequence, while liquid-vapor interface vaporization occurred throughout. The pressure decay characteristics for this test can be found in figure 4(a), while the variation of vent mass flow can be found in

figure 4(b). In figure 4(c) the variation of the temperature in the vicinity of the liquid surface with time is shown.

Test 3

The initial conditions for this test were a 30 percent initial vapor volume, a low average vent rate of 0.20 gram per second, and an applied acceleration of 1.96 centimeters per second squared which resulted in a system Bond number of 9. The conditions in this test differ from test 1 only in the average mass flow rate through the vent. The variation in vent mass flow rate for this particular test is shown graphically in figure 5(b). Some boiling was observed in this test; it appeared to start at 3.1 seconds. The amount of generated vapor was estimated at approximately 1 cubic centimeter, and 27 vapor bubbles appeared. The depressurization time history for this test is shown in figure 5(a), while the variation in the vapor temperature in the vicinity of the liquid-vapor interface is shown in figure 5(c).

Test 4

In test 4, the lowest average mass flow rate was obtained. The average value was calculated to be 0.04 gram per second (see fig. 6(b)). The system Bond number was 9 (as in tests 1 and 3) and the percent vapor volume was 30. A small amount of bulk vapor generation was observed in this test. Boiling started at about 3.35 seconds and seven vapor bubbles, with an estimated volume of 3 cubic centimeters were generated. A plot of the pressure response in the ullage during venting is shown in figure 6(a), while the variation of the vapor temperature adjacent to the interface is shown in figure 6(c).

Test 5

In test 5, the percent vapor by volume was 30 and the system acceleration was 13.7 centimeters per second squared. This acceleration resulted in a Bond number of 63 and provided the flattest liquid-vapor interface. The average mass flow rate through the vent (see fig. 7(b)) was 0.47 gram per second and, hence, was nearly identical to that observed in tests 1 and 2. In this test, large vapor bubbles were generated with boiling being initiated at approximately 2.45 seconds into the drop. An estimated 11 cubic centimeters of vapor were generated in this test. The pressure decay rate is indicated in figure 7(a), while the variation of temperature in the vicinity of the liquid-vapor interface is shown in figure 7(c).

Test 6

A high percent vapor volume (70 percent by volume) was examined in this test. The system Bond number was 9 as in tests 1, 3, and 4, and the vent mass flow rate was essentially the same as in tests 1, 2, and 5. In test 6, bulk vapor generation occurs relatively late during the venting sequence (approximately 3.2 sec). An estimated 3 cubic centimeters of vapor was generated during the 3 seconds of venting, and 23 very small bubbles were generated. The pressure decay in the ullage is shown graphically in figure 8(a). It is seen that the pressure decays from 8.4 to 7.5 newtons per square centimeter, or 0.9 newton per square centimeter in 3 seconds. The variation of vent mass flow rate is displayed in figure 8(b).

Test 7

In test 7, the vent mass flow rate was the highest. It had an initial value of 0.95 gram per second (see fig. 9(b)). The average value was calculated to be 0.77 gram per second. The percent vapor volume was 30 and the system Bond number was 9. This experimental test resulted in the largest amount of vapor generated in the bulk liquid due to boiling. Bulk vapor generation was observed to start at approximately 2.1 seconds and an estimated 47 cubic centimeters of vapor was generated. Nine large vapor bubbles were observed. The pressure decay characteristics for this test are shown in figure 9(a). The measured temperature decrease in the vicinity of the liquid-vapor interface was more than twice as great for this test than for any other test (see fig. 9).

DISCUSSION OF RESULTS

The previous description of the tests of venting initially saturated Refrigerant 11 indicates that, during a venting sequence, both the tank internal pressure and temperature of the vapor in the vicinity of the liquid-vapor interface decrease with time as expected. Secondly, the mass flow rate through the vent also decreases with time. Significant interface vaporization occurred throughout the venting sequence in contrast to the tests of Larkin and Bowman (ref. 6) in which the interface vaporization was insignificant because of the high vent rates tested. With the exception of test 2, bulk boiling was also observed; however, it always took some finite time prior to the start of bulk boiling. Three variables had an effect on the venting phenomena as follows.

Bond Number

The effect of varying the system Bond number appears to be twofold. First, the Bond number (for the case of a liquid which has a zero-degree contact angle in contact with the container surface) determines the shape of the liquid-vapor interface. As a result, the Bond number can be viewed as a measure of the exposed surface area during venting. Secondly, the gravity level, which is included in the Bond number aR^2/β determines to an extent the amount of heat transferred to the liquid-vapor interface by convection. It is noted that under complete weightless conditions heat is transferred to the liquid-vapor interface only by conduction. The mass transferred across the interface in the form of vapor will depend upon the exposed surface area and the rate at which heat is transferred to it (ref. 7). It can be recalled that three of the previously discussed tests had identical initial vapor volumes and approximately the same average vent mass flow rates. The results indicated that the test at a Bond number of 63 resulted in 11 cubic centimeters of generated vapor in the bulk and bulk boiling was initiated at 2.45 seconds. The test with the Bond number of 9 resulted in 16 cubic centimeters of vapor and bulk boiling was initiated at 2.8 seconds. The zero Bond number test resulted in no bulk boiling.

It is concluded that the largest Bond number (Bo = 63) would result in more vapor generation in the bulk than the zero Bond number test, provided the initial temperatures and pressures were identical, due primarily to the fact that there would be half as much surface area from which evaporation could take place. When comparing the two low Bond number tests with each other, it must be realized that area and gravity changes for increasing or decreasing Bond numbers have compensating effects with respect to the mass transferred across the liquid-vapor interface.

Vent Rate

In four of the tests, the percent vapor volume was 30 and the system Bond number was 9. The average vent mass flow rates were 0.04, 0.20, 0.53, and 0.77 gram per second. The results indicate that the most vapor generated in the bulk was in the test with the largest vent rate, 0.77 gram per second (48 cc). Sixteen cubic centimeters of vapor was generated in the bulk at a vent rate of 0.53 gram per second. Three cubic centimeters of vapor was generated at the lowest average vent mass flow rate of 0.04 gram per second while 1 cubic centimeter of vapor was generated at a vent mass flow rate of 0.20 gram per second. This last result was somewhat surprising because of the difference in mass vent flow rates. However, the test with the vent rate of 0.04 gram per second did start to boil later than the test with the vent rate of 0.20 gram per second. In fact, boiling started at 2.1, 2.8, 3.1, and 3.3 seconds for tests with vent mass

flow rates of 0.77, 0.53, 0.20, and 0.04 gram per second, respectively.

Higher vent rates result in a generally large generation of vapor in the bulk liquid and bulk boiling occurs sooner. This conclusion appears reasonable since larger vent rates produce a greater rate of pressure decrease. Therefore, for any two systems identical except for the vent mass flow rate at any instant of time after the initiation of venting, the liquid surface temperature will be lower for the case where the depressurization rate is greater. Since it normally takes a finite amount of superheat prior to the start of boiling, the previous conclusion appears physically reasonable.

Percent Vapor Volume

The effect of percent vapor volume on the venting of saturated vapor can be seen if the tests with identical Bond numbers and vent mass flow rates are compared. In the test with a 70 percent vapor volume, the majority of bulk boiling started at approximately 3.2 seconds and 23 small vapor bubbles were formed with a total vapor volume of 3 cubic centimeters. In the test with a 30 percent vapor volume, boiling started at 2.8 seconds and 16 cubic centimeters of vapor was generated in the bulk. At lower percent vapor volumes the pressure decay will be greater and this will result in a larger difference between the temperature of the liquid bulk and the liquid surface. As a result, bulk boiling will occur sooner and result in a larger volume of generated vapor.

CONCLUDING REMARKS

An experimental investigation of venting initially saturated Refrigerant 11 from a cylindrical container (15-cm diameter) under reduced gravitational conditions was conducted in the Lewis Research Center's 5-Second Zero-Gravity Facility. Refrigerant 11 possessed a near-zero-degree contact angle on the container surface. The system Bond numbers studied were 0, 9, and 63, such that the liquid-vapor interface varied from highly curved to nearly flat.

The results show that, during venting, significant vaporization occurs both in the liquid bulk (bulk boiling) and at the liquid-vapor interface. The temperature of the liquid in the immediate vicinity of the liquid-vapor interface was found to decrease during a venting sequence while the bulk temperature remained constant. Bulk boiling did not start until some time after vent initiation. When bulk boiling occurred, the generated vapor tended to remain below the liquid-vapor interface thereby moving the interface towards the vent.

The start of bulk boiling and the amount of vapor generation was found to be dependent on the vent rate. Similarly, the start of bulk boiling and the amount of vapor generation was found to depend on the percent vapor volume. The effect of changing the system Bond number appears to be more complex. It is concluded only that the low Bond number tests result in more vapor generated in the bulk than the zero Bond number tests. The effect of decreasing Bond number on the venting process has two effects; first, a change in the exposed surface area to venting and secondly, a change in the heat transfer mode (i.e., conduction against convection at the liquid-vapor interface).

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113-31.

APPENDIX - APPARATUS AND PROCEDURE

Test Facility

The experiment data for this study were obtained in the 5- to 10-Second Zero-Gravity Facility at the Lewis Research Center. A schematic diagram of this facility is shown in figure 10. The facility consists of a concrete-lined 8.5-meter-diameter shaft that extends 155 meters below ground level. A steel vacuum chamber, 6.1 meters in diameter and 143 meters high, is contained within the concrete shaft. The pressure in this vacuum chamber is reduced to 13.3 newtons per square meter by utilizing the Center's wind tunnel exhaust system and an exhauster system located in the facility.

The ground-level service building has, as its major elements, a shop area, a control room, and a clean room. Assembly, servicing, and balancing of the experiment vehicle are accomplished in the shop area. Tests are conducted from the control room (see fig. 11) which contains the exhauster control system, the experiment vehicle predrop checkout and control system, and the data retrieval system. Those components of the experiment which are in contact with the test fluid are prepared in the facility's class 10 000 clean room. The major elements of the clean room are an ultrasonic cleaning system (fig. 12(a)) and a class 100 laminar-flow station (fig. 12(b)) for preparing those experiments requiring more than normal cleanliness.

Mode of operation. - The Zero-Gravity Facility has two modes of operation. One is to allow the experiment vehicle to free-fall from the top of the vacuum chamber, which results in nominally 5 seconds of free-fall time. The second mode is to project the experiment vehicle upwards from the bottom of the vacuum chamber by a high pressure pneumatic accelerator located on the vertical axis of the chamber. The total up-and-down trajectory of the experiment vehicle results in nominally 10 seconds of free-fall time. The 5-second mode of operation was used for this experimental study.

In either mode of operation, the experiment vehicle falls freely; that is, no guide wires, electrical lines, and so forth are connected to the vehicle. Therefore, the only force (aside from gravity) acting on the freely falling experiment vehicle is due to residual air drag. This results in an equivalent gravitational acceleration acting on the experiment which is estimated to be of the order of 10^{-5} g maximum.

Recovery system. - After the experiment vehicle has traversed the total length of the vacuum chamber, it is decelerated in a 3.6-meter-diameter, 6.1-meter-deep container which is located on the vertical axis of the chamber and filled with small pellets of expanded polystyrene. The deceleration rate (averaging 32 g's) is controlled by the flow of pellets through the area between the experiment vehicle and the wall of the deceleration container. This deceleration container is mounted on a cart which can be retracted prior to utilizing the 10-second mode of operation. In this mode of operation,

the cart is deployed after the experiment vehicle is projected upward by the pneumatic accelerator. The deceleration container mounted on the cart is shown in figure 13.

Experiment Vehicle

The experiment vehicle consisted of three basic sections (see fig. 14). A thrust system section, which is contained in a conical base, an experiment section, which is housed in a cylindrical midsection, and a telemetry section which is contained in the top fairing.

Thrust system. - The conical base of the experiment vehicle contains the cold-gas thrust section and is capable of producing thrusts ranging from 13 to 130 newtons for time durations in excess of 5 seconds. The acceleration was calculated from the calibrated thrust by measuring the package weight. Prior to the installation on the experiment vehicle, the thrust system was calibrated on a static thrust calibration stand located in the facility vacuum chamber. The calibration was conducted at pressure levels corresponding to test-drop conditions. A null-balance, load-cell system was used to record the thrust time history as a function of thrust nozzle inlet pressure and nozzle size.

Telemetry system. - The on-board telemetry system is an FM/FM system with 18 continuous channels. During a test drop, telemetry is used to continuously record thrust nozzle inlet pressure, two low-gravity accelerometers, and other parameters pertinent to the experiment.

Experiment. - The experiment section consisted of the test container tray plus electrical power and control system equipment mounted in the cylindrical section of the experiment vehicle. The test container tray included the test container, camera, and lighting and timing systems. The vent system, which included a solenoid valve and various sized orifices, was mounted above the test container. The solenoid valve opened during the test drop and vapor was vented to the low pressure test chamber. The ensuing venting procedure was recorded by a high speed motion picture camera. Elapsed time was obtained from a digital clock.

Test Procedure

Cleaning, filling, and hermetic sealing of the test containers was conducted in the Zero-Gravity Facility's clean room (fig. 12). Contamination of the liquid and cylinder, which could alter the surface tension and contact angle, was carefully avoided. The test cylinders were cleaned ultrasonically in a detergent-water solution, rinsed with a

distilled-water-methanol solution and dried in a warm air dryer. The test cylinders were rinsed with the test liquid, filled to the desired liquid depth, and sealed to prevent contamination. They were then mounted on the test container tray. During the test, a predetermined time increment was allowed so that the liquid-vapor interface could approach its low-gravity equilibrium shape. After the formation time, the solenoid valve was opened and the vapor vented to vacuum for 3 seconds.

Electrical timers on the experiment vehicle are set to control the initiation and duration of all functions programmed during the drop. The experiment vehicle is balanced about its vertical axis to ensure an accurate drop trajectory and thrust alinement with respect to the experiment tank. Accurate thrust alinement is necessary to provide an axisymmetric, equilibrium liquid-vapor interface shape.

The vehicle is then positioned at the top of the vacuum chamber as shown in figure 15. It is suspended by the support shaft on a hinged-plate release mechanism. During vacuum chamber pumpdown and prior to release, monitoring of experiment vehicle systems is accomplished through an umbilical cable attached to the top of the support shaft. Electrical power is supplied from ground equipment. The system is then switched to internal power a few minutes before release. The umbilical cable is remotely pulled from the support shaft 0.5 second prior to release. The thrust system is activated 0.2 second before release to allow the thrust to reach steady-state conditions. The vehicle is released by pneumatically shearing a bolt that holds the hinged plate in the closed position. No measurable disturbances are imparted to the experiment vehicle by this release procedure.

The total free-fall test time obtained in this mode of operation is 5.16 seconds. Approximately 0.13 second before the experiment vehicle enters the deceleration container, the thrust system is shut down to avoid dispersing the deceleration material. During the test drop, the vehicle's trajectory and deceleration are monitored on closed-circuit television. Following the test drop, the vacuum chamber is vented to the atmosphere and the experiment vehicle is returned to ground level.

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TABLE I. - SUMMARY OF TEST PARAMETERS

Test number	Percentage vapor by volume	System acceleration, cm/sec^2	Bond number	Initial mass vapor, g	Average mass flow rate, g/sec	Percentage ullage volume per second	Total mass vented, g	Estimated bulk vapor generation	
								Volume, cc	Mass, g (a)
1	30	1.96	9	7.7	0.53	6.9	1.58	16	0.077
2	↓	0	0	7.7	.53	6.9	1.60	0	0
3		1.96	9	7.2	.20	2.5	.60	1	.005
4		1.96	9	7.2	.04	.6	.13	3	.014
5		13.7	63	7.1	.47	6.6	1.40	11	.048
6	70	1.96	9	16.8	.52	3.9	1.56	3	.012
7	30	1.96	9	6.7	.77	11.5	2.31	47	.188

[a]Based on average density during venting.

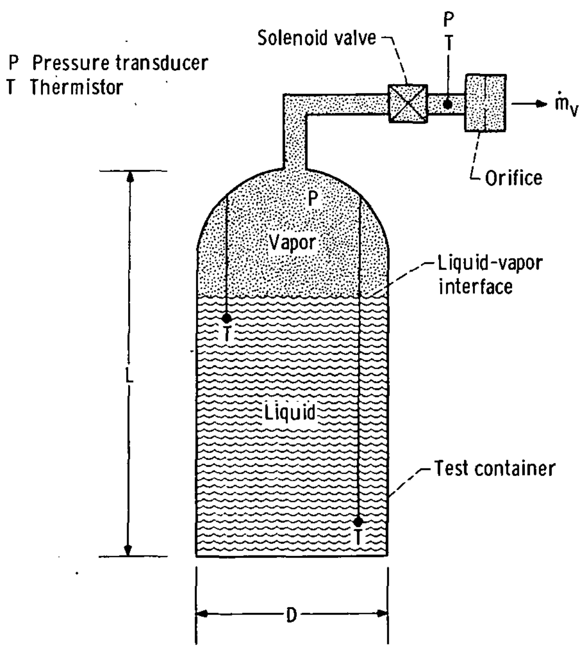
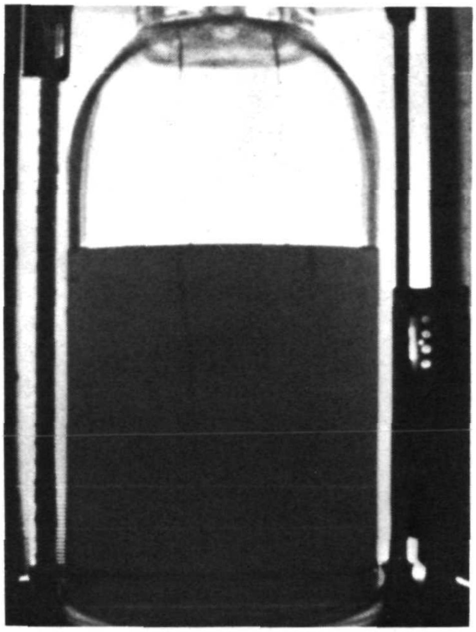
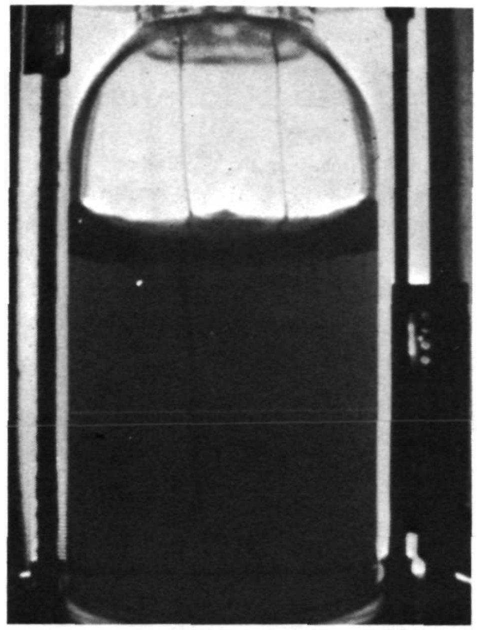


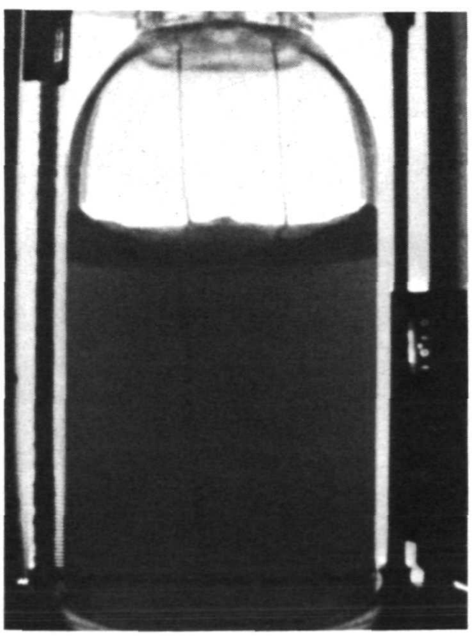
Figure 1. - Vent system in cylindrical containers.



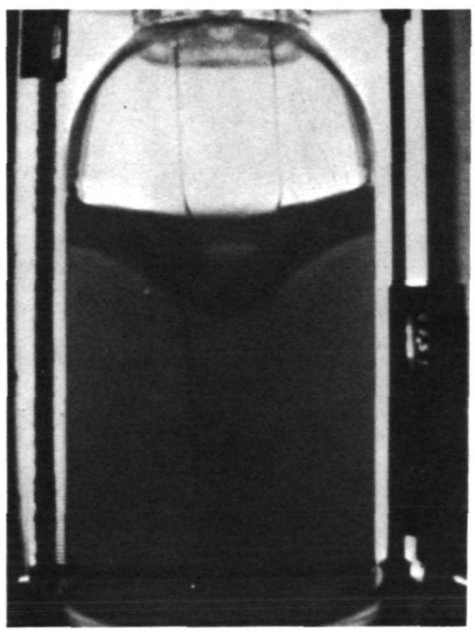
(a) Normal-gravity initial condition. Time from initiation of test t = 0 second.



(b) Formation of low-gravity equilibrium interface. Time from initiation of test t = 1 second.

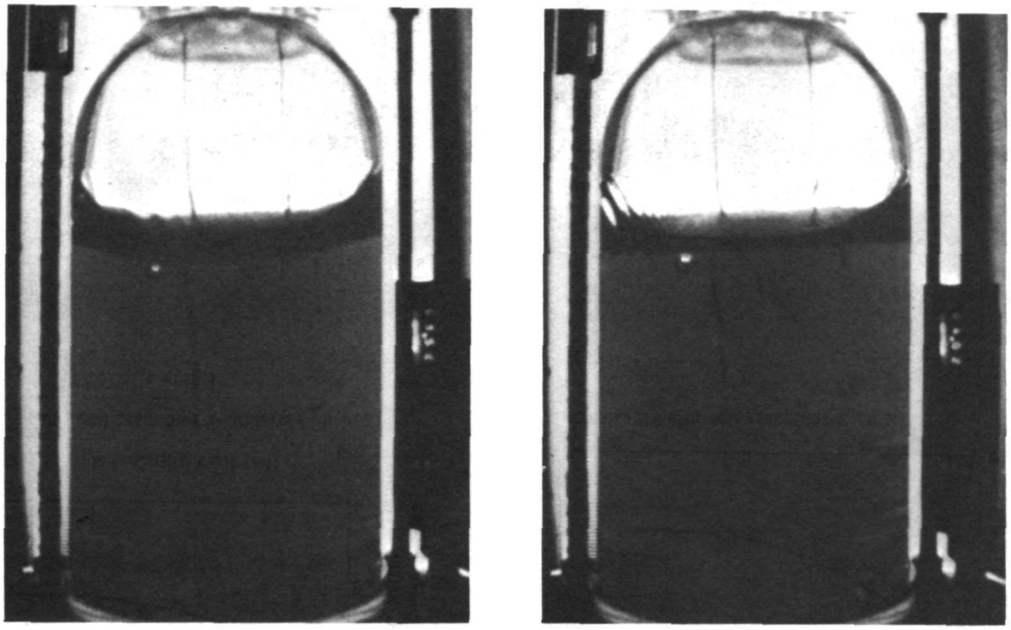


(c) Venting initiated. Time from initiation of test t = 1.01 seconds.



(d) Boiling occurs near container bottom. Time from initiation of test t = 2.5 seconds.

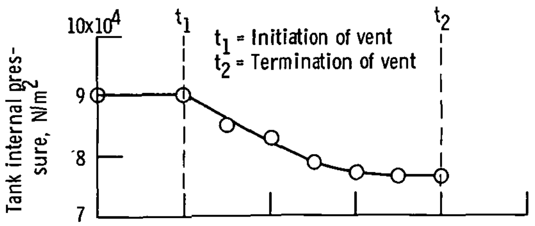
Figure 2. - Response of liquid during venting for selected data run (test 1).



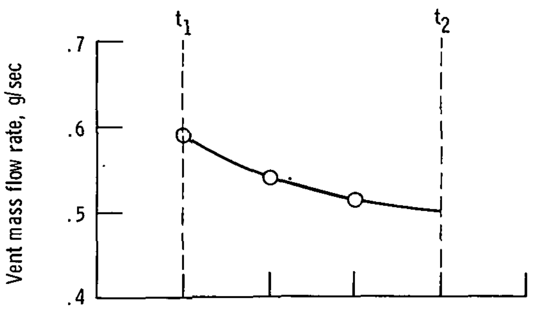
(e) Bulk boiling and surface vaporization occurring simultaneously. Time from initiation of test t = 3.5 seconds.

(f) Configuration prior to termination of vent. Time from initiation of test t = 4 seconds.

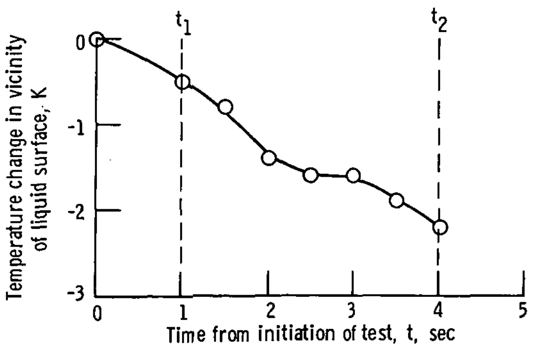
Figure 2. - Concluded.



(a) Variation of tank internal pressure with time.

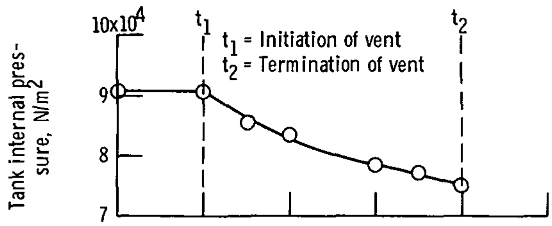


(b) Variation of vent mass flow rate with time.

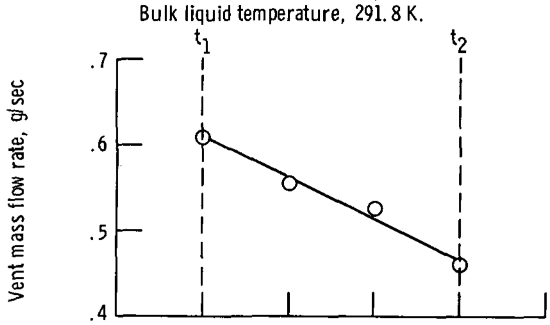


(c) Variation of temperature in vicinity of liquid surface with time.

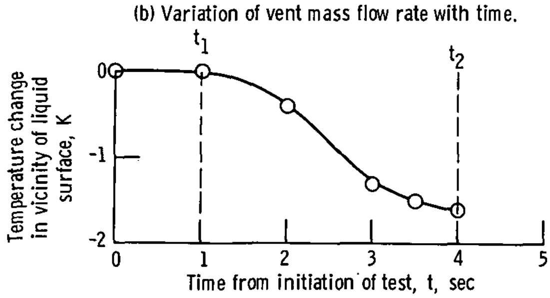
Figure 3. - Test 1.



(a) Variation of tank internal pressure with time. Bulk liquid temperature, 291.8 K.



(b) Variation of vent mass flow rate with time.



(c) Variation of temperature in vicinity of liquid surface with time.

Figure 4. - Test 2.

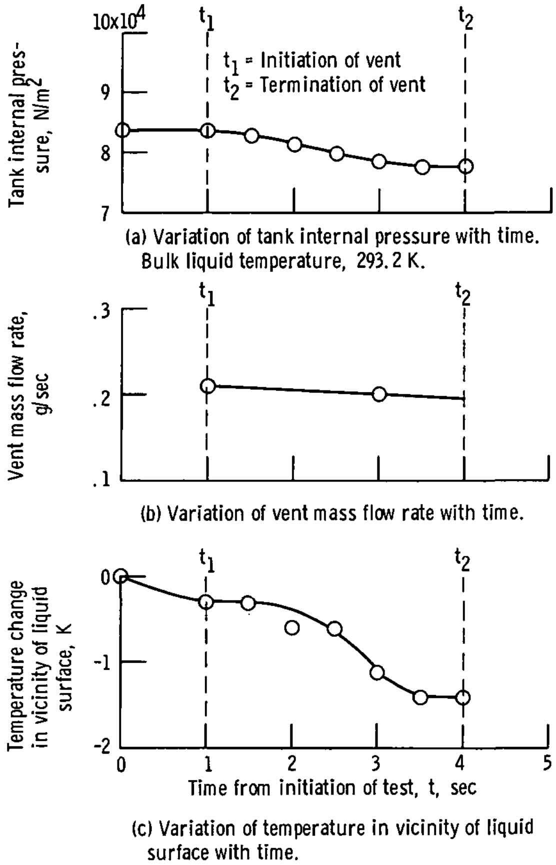


Figure 5. - Test 3.

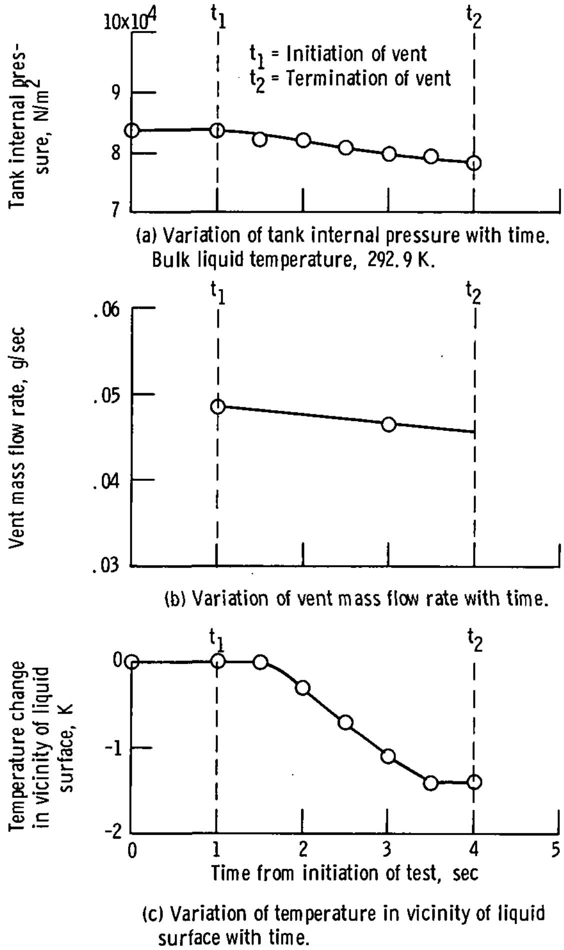
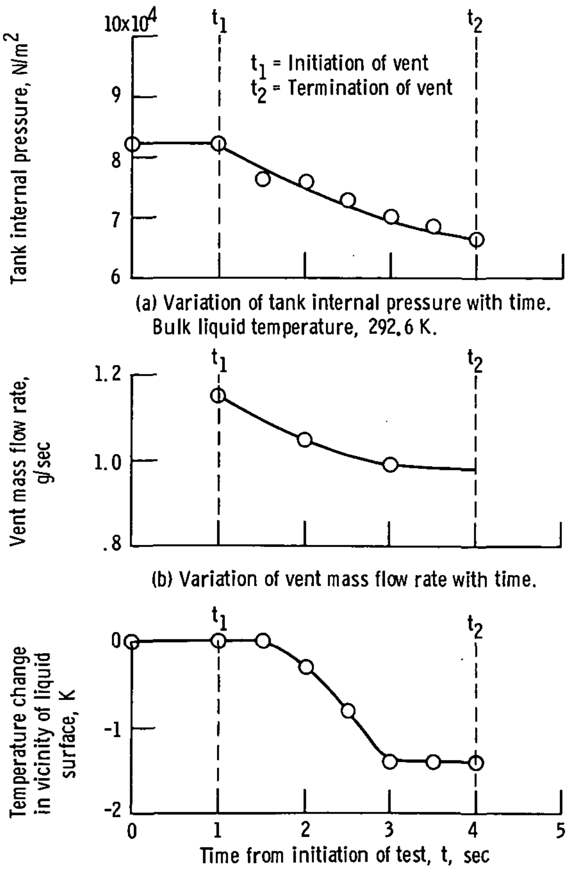


Figure 6. - Test 4.

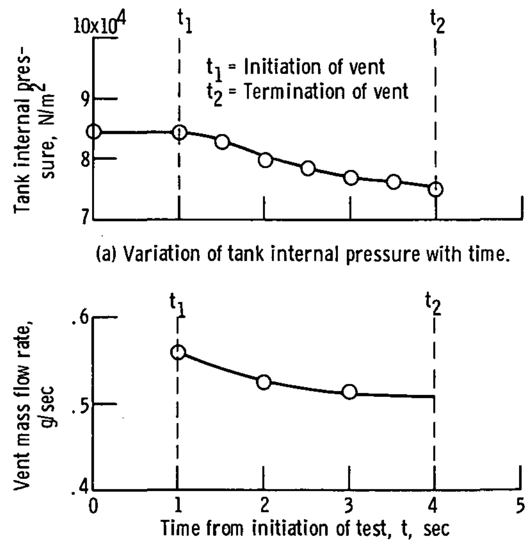


(a) Variation of tank internal pressure with time. Bulk liquid temperature, 292.6 K.

(b) Variation of vent mass flow rate with time.

(c) Variation of temperature in vicinity of liquid surface with time.

Figure 7. - Test 5.



(a) Variation of tank internal pressure with time.

(b) Variation of vent mass flow rate with time.

Figure 8. - Test 6.

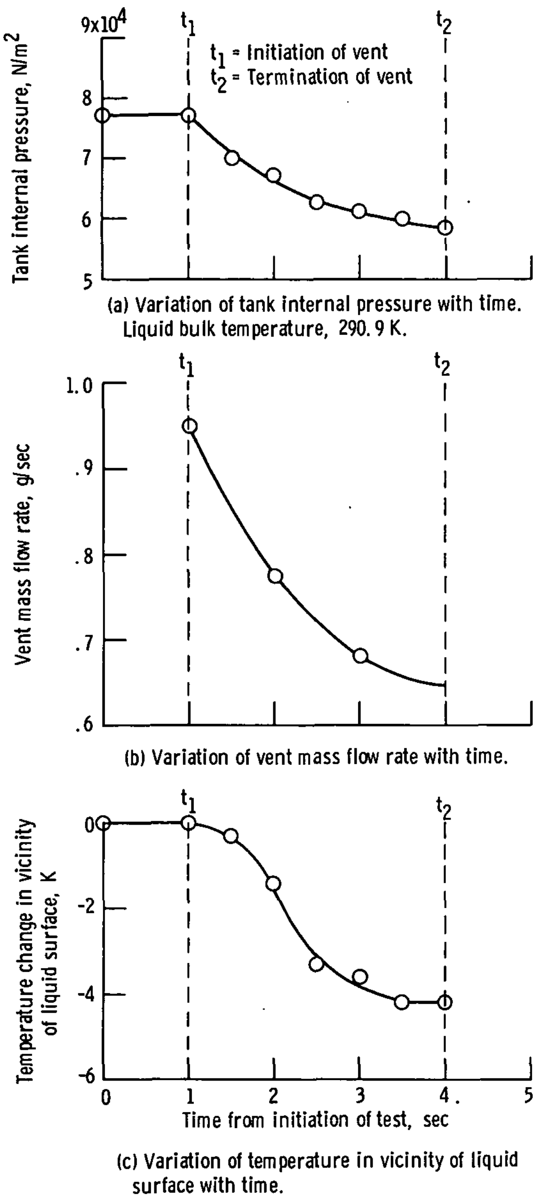


Figure 9. - Test 7.

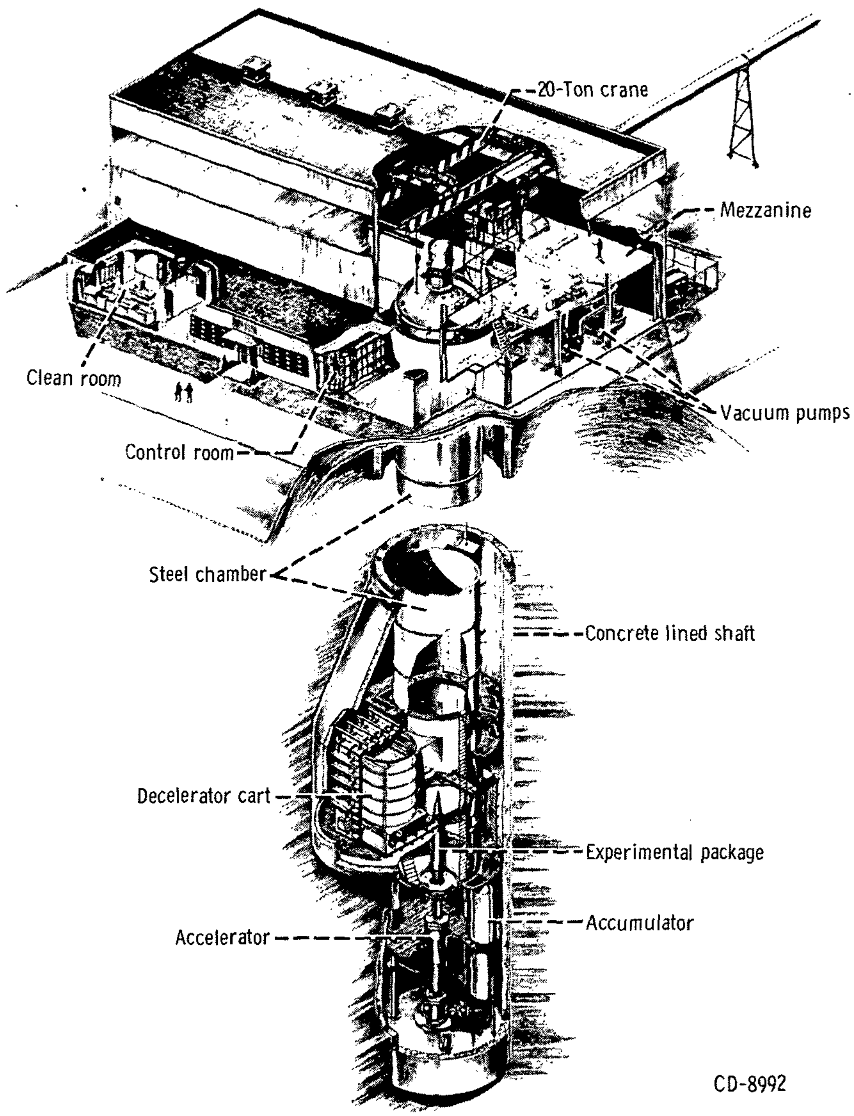


Figure 10. - Schematic diagram of 5- to 10-Second Zero-Gravity Facility.

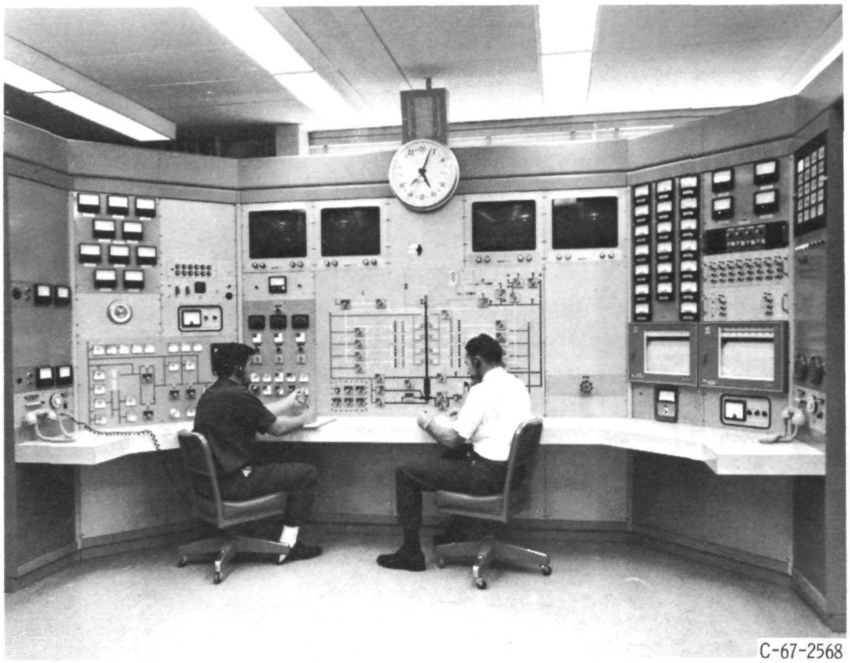
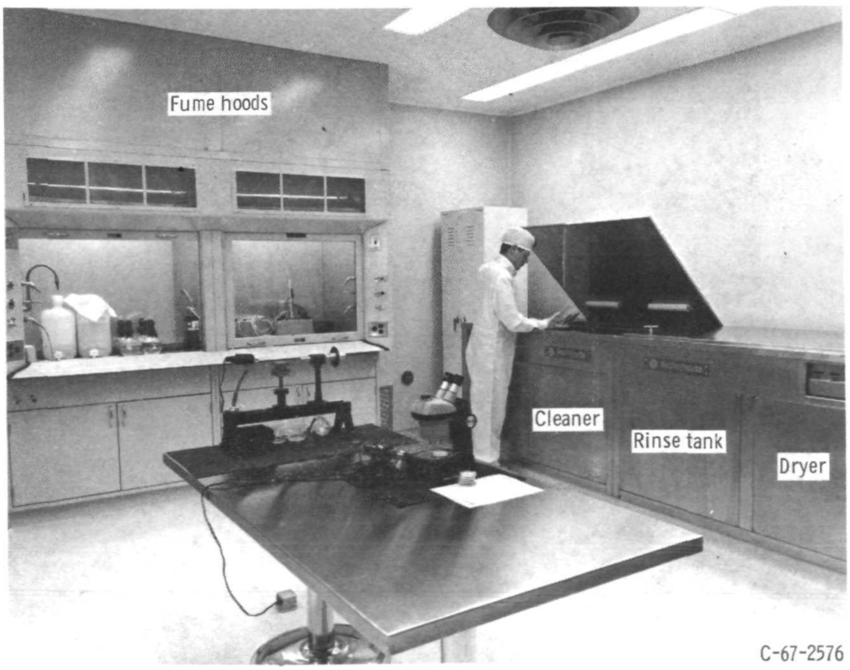
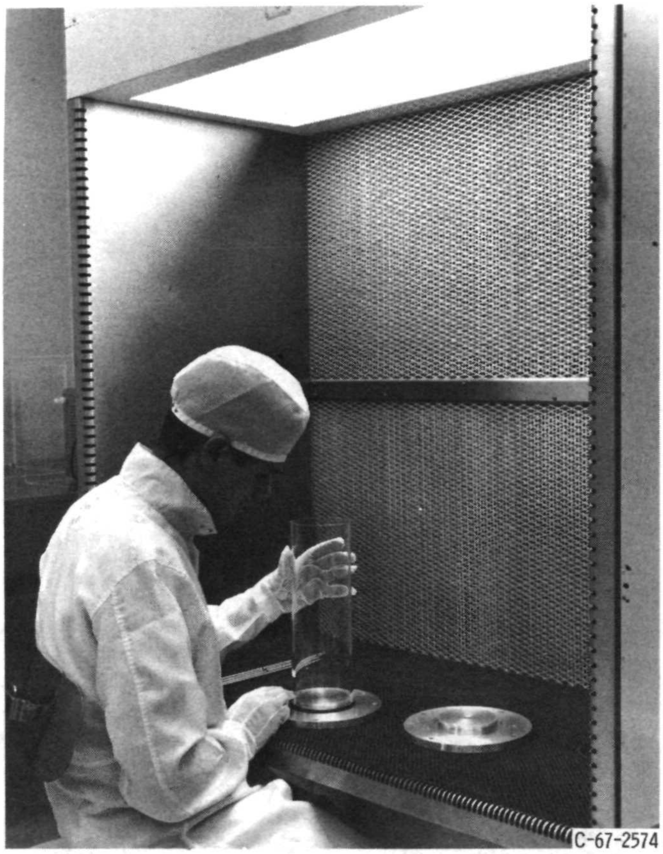


Figure 11. - Control room.



(a) Ultrasonic cleaning system.

Figure 12. - Facility clean room.



(b) Laminar flow work station.

Figure 12. - Concluded.

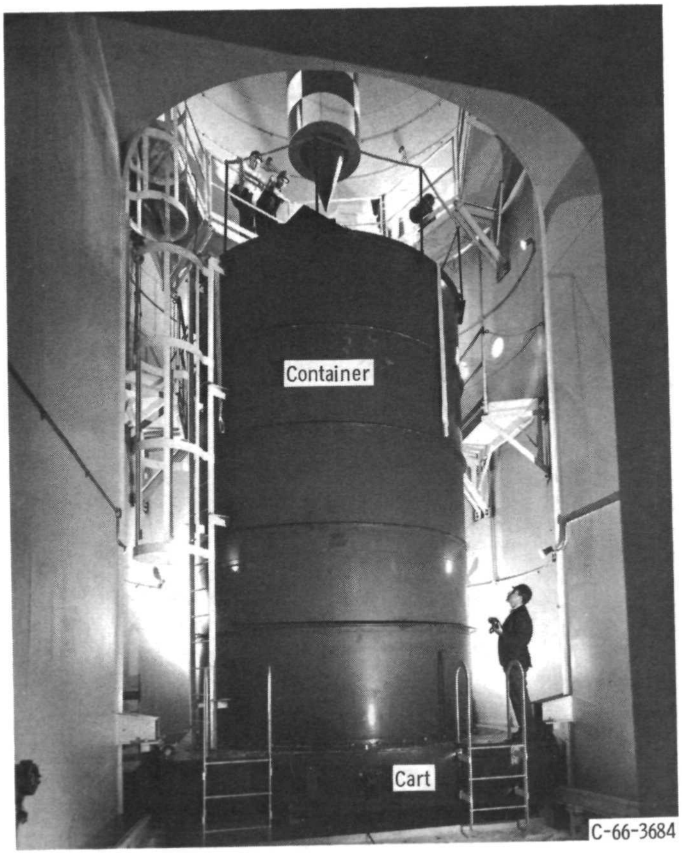


Figure 13. - Deceleration system.

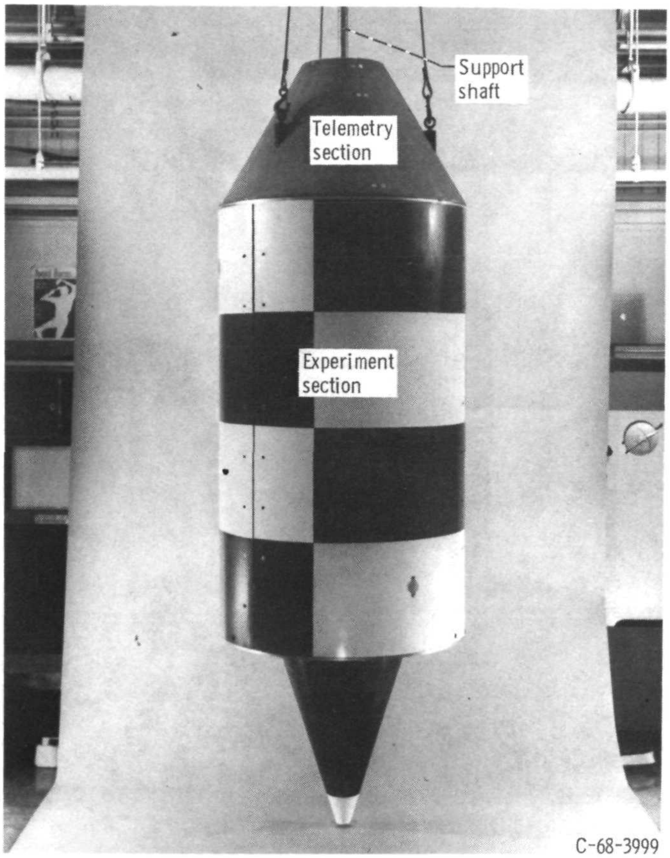


Figure 14. - Experiment vehicle.

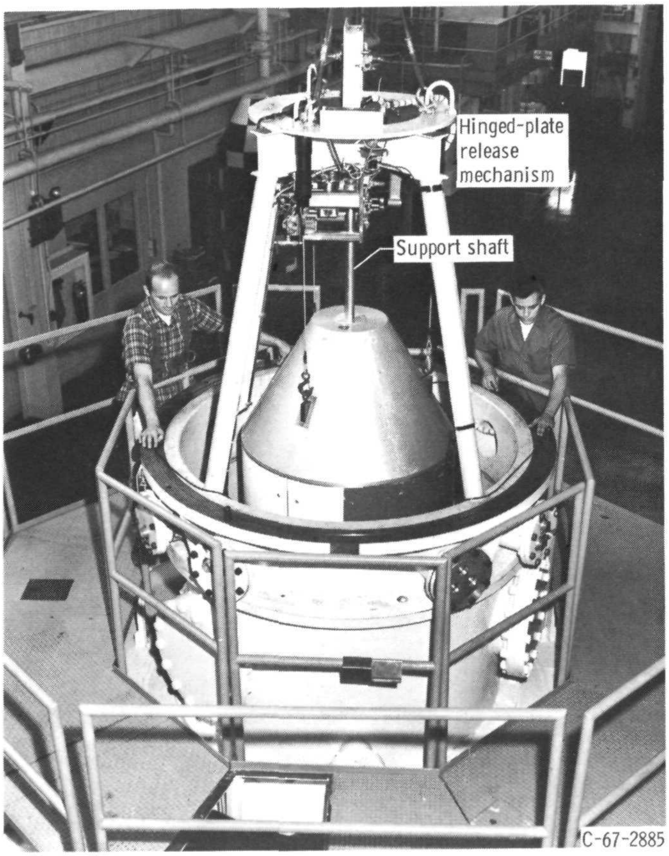


Figure 15. - Vehicle position prior to release.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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